Low-frequency Variability of the Climate System: A Modal Approach

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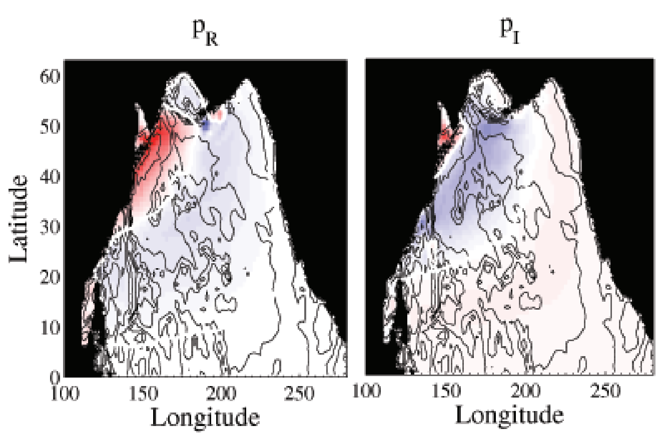
The Earth's climate system displays variability on many time scales. Of particular interest are the decadal (~20 yrs) and multidecadal (~60 yrs) climate cycles that are present in the North Atlantic and North Pacific Oceans; understanding the origin of this variability is crucial for detecting and attributing climate change, and may increase our skills in predicting climate many years in advance.

Here we investigate whether internal ocean oscillations may be responsible for low-frequency variability in the North Pacific. Such oscillations, called basin modes, are predicted by theory, but their existence has not been confirmed from observations,nor in comprehensive climate models. We use advanced statistical and numerical techniques to identify free oscillations in the North Pacific Ocean in a coupled climate model, and study their excitation and their influence on the North Pacific climate system.

Fig. 1. Basin mode of the North Pacific Ocean. Shown is a linear eigenmode of the North Pacific basin. The model represents the North Pacific Ocean as a superposition of two motionless layers of different density. Deviations in the depth of the upper layer (shading) are superimposed on ocean depth contours. The patterns pR and pI represent two subsequent phases of an oscillation, and define an oscillatory cycle according to the sequence pR $\rightarrow$ pI $\rightarrow$ - pR $\rightarrow$ - pI $\rightarrow$ pR, etc. The oscillation therefore shows northwestward propagation of deviations in upper layer depth.



The climate system is a highly complex system, as it consists of several components (ocean, atmosphere, cryosphere, etc.) that strongly influence each other. Apart from external forcing factors, like changes in solar insolation, volcanic eruptions, or increasing levels of carbon dioxide due to human activity, the climate system generates variability on its own. The best-known example is the El Nino phenomenon that dominates climate variability on interannual time scales (~4 to 5 years).

In recent decades it has become increasingly clear that the climate system also exhibits variability on decadal (~20 years) and multidecadal (~60 years) time scales. The Pacific Decadal Oscillation (PDO) [1] and Atlantic Multidecadal Oscillation (AMO) [2], for example, are cycles in the sea surface temperatures (SST) of the North Pacific and North Atlantic Oceans, respectively, and have a significant impact on drought cycles in the US Southwest [3].

The origin of these low-frequency climate cycles is still under intense scrutiny; understanding these modes of variability is an important charge to climate scientists. First of all, the presence of this low-frequency variability makes it harder to assess how much of the recent global warming can be attributed to anthropogenic forcing. Second, understanding the dynamics may enable us to improve climate predictions.

Most theories of low-frequency climate variability ascribe a key role to the ocean. The ocean's inertia (both thermal and mechanical) is about three orders of magnitude larger than that of the atmosphere, so the ocean responds very sluggishly to the synoptic activity of the atmosphere (storm systems, etc.). In fact, the simplest theory (the so-called null hypothesis) explains the PDO simply as a slow response of the ocean to relentless nudging by the atmosphere (a so-called red noise response). However, this theory appears to be insufficient to explain the specific 20-year time scale that is found in the Pacific climate system. A competing (or complementary) hypothesis therefore ascribes a more active role to the ocean, by posing that the atmospheric nudging excites free, internal oscillations in the ocean. Such oscillations, called basin modes, are predicted by models that represent the basic dynamics of ocean circulation [4] (Fig. 1), but are hard to observe in the real ocean, or even in more comprehensive ocean models.

A project funded by the National Science Foundation, and executed jointly at the New Mexico Consortium and LANL, aims to detect such basin modes in climate models, and determine their involvement in low-frequency climate variability. The project uses advanced statistical methods to detect oscillatory variability in the ocean. The subject of analysis is the climate as represented by the third carnation of the Community Climate System Model (CCSM3). CCSM3 is a top-tier climate

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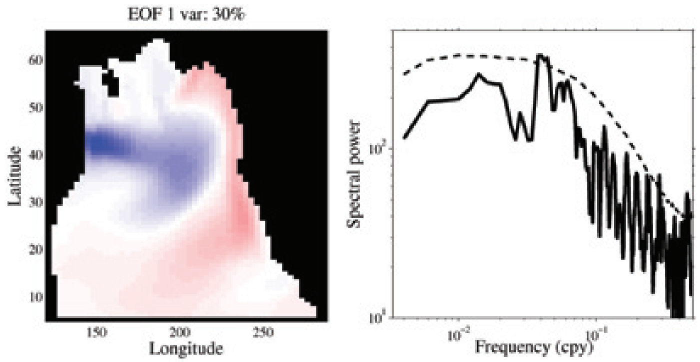

Fig. 2. Dominant mode of variability (Empirical Orthogonal Function, or EOF) of the SST in the North Pacific, in a simulation of the CCSM3. Left: Spatial pattern, showing cold temperatures in the central North Pacific, and warm waters in the eastern and southern North Pacific. This pattern closely matches the PDO, as defined from observations. Right: Power spectrum of the associated time series, showing a significant spectral peak at 22 years.

model that has made substantial contributions to the fourth assessment report (AR4) of the Intergovernmental Panel on Climate Change (IPCC).

North Pacific SSTs in this model display variability that closely resembles the PDO from observations (Fig. 2). In addition, there appears to be a preferred periodicity of about 20 years, also in agreement with the observations. We can therefore assume that the processes responsible for generating the variability in this model are also active in the real ocean.

To find the dynamical origin of this variability, variations in SST and the ocean's interior density field (represented by a novel metric referred to as ADZC) are subjected to a so-called multivariate Principal Oscillation Pattern (POP) analysis [5]. A POP analysis extracts oscillatory signals from noisy data. Figure 3 shows the spatial structure of the dominant oscillatory mode. The two panels represent two distinct phases of the oscillation (referred to as pR and pI) that define an entire oscillatory cycle. The signature of the PDO is clearly visible in the SST field, suggesting that this oscillatory mode is indeed responsible for the model representation of the PDO. Indeed, the oscillation period associated with the POP is 23 years.

The mode has a clear expression in the subsurface density field. Current investigations aim to determine 1) whether this is indeed the signature of a real basin mode, and 2) how this variability in the interior ocean is communicated to the atmosphere in order to generate a signal in the climate system. If this is a basin mode (and not simply the filtered response to atmospheric stochastic forcing) then we would know another explanation for decadal oscillations in the North Pacific Ocean, and perhaps predict surface Pacific Ocean conditions several years in advance.

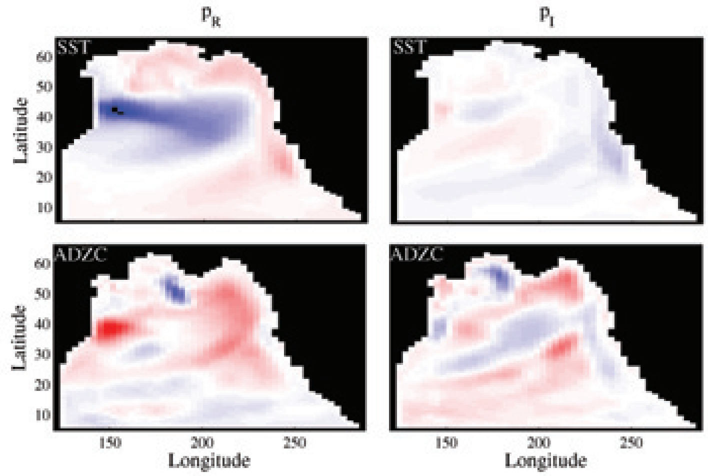

Fig. 3. Dominant oscillatory mode for the periods between 15 and 25 years. Upper plot shows the expression in sea-surface temperature (SST), while lower plots show ADZC, a metric representing the ocean's interior density field. As in Fig. 1, the two patterns represent two phases of the oscillatory cycle. The oscillation period is 23 years.

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